LATE STAGE ACTIVITY OF LARGE VOLCANOES ON VENUS

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INTRODUCTION. Several distinctive morphologic classes occur among large volcanoes on Venus [1]. Many of these differences are consistent with the details of interaction with surrounding structural patterns, and variations in late stage activity. The presence of large volcanoes is significant in itself, however, because specific conditions in the feeding reservoir must exist in order for a magmatic center to give rise to edifice growth. In this study we review one of those conditions by examining some possible implications of the typical observed relief characteristics of large volcanoes on Venus.

VOLCANO STRATIGRAPHY. Detailed stratigraphy from mapping of individual large volcanoes [2] indicates that a there is a recurring theme in which early eruptions are voluminous and contribute to widespread regional plains development, and late eruptions are increasingly digitate and radiate from a common vent. We interpret these stratigraphic variations as a record of change in style of eruption over the lifetime each magmatic center.

EDIFICE VOLUME DISTRIBUTION. The observed relief characteristics of large volcanoes records the distribution of volume in a “characteristic” eruption during actual construction of the edifice. The observed population of large volcanoes on Venus consist frequently of regular straight-sloped cones [1, 3] of relatively shallow slope. In order to accumulate a cone of this form, the volume added to the surface about the vent from each eruption, or as a long term average, must have a specific distribution given by

$dV = 2^{1}r[f(R)]dr$.

$f(R)$ is a “shape” function that describes the profile of the volcano with distance r from the vent and is of the form

$f(R)= k - \gamma r^{ß}$.

For a straight cone of unit height, k and ß are unity and γ is the slope. But for more complex profiles, ß may itself be a complex variable. In order to attain the shape of a straight-sloped right cone (Fig. 1A) typical of large volcanoes on Venus, the ideal or "average" volume distribution with distance from the vent for each eruption must therefore be

$dV/dr = 2^{1}(r - \gamma r^{2})$.

Most of the volume of a given shield volcano therefore is in the mid flank region, with smaller incremental volumes in the vent region and distal flanks (Fig. 1A). This is a key observation that establishes importance one of the primary conditions of eruption necessary for construction of any edifice: Until “average” shield building flow unit or flow field accumulated during a single eruption begins following this distribution (Fig. 1A) , an edifice does not begin forming.

ERUPTION VOLUME DISTRIBUTION. The mechanism controlling eruptions such that they attain this distribution is the central question. Stochastic variations over time in the length of straight monotonous flows of uniform width and thickness are not sufficient for the generation of straight sloped edifices; variations in the plan shape, thickness, or both, with distance from the vent are required. Volume effusion rate is likely to be the most variable characteristic between eruptions, followed by secular variations in magma chemistry throughout the history of an individual magmatic center. For basaltic magmas the problem therefore reduces to the conditions responsible for variations in volume of flow fields with distance from the source vent in a typical flow or flow field. Several models may be applicable.

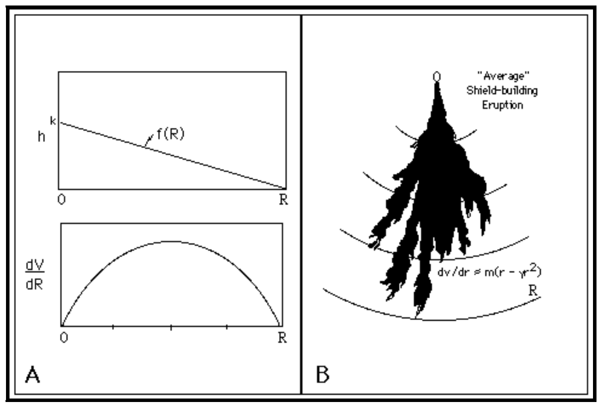

Figure 1. (A) Distribution of volume in a straight-sloped cone. (B) Possible shape of "average" flow field on volcano flank responsible for volume distribution in (A). Concentric arcs represent schematic topographic contours on the flanks of a shield volcano of radius R.

Variations in volume of flow fields with distance from the source vent have been noted from Mt. Etna [4] and have been attributed to variations in effusion rate during the course of a single eruption. The theoretical basis for length/effusion rate relationship has been explored and is related to the dimensionless Grätz number relating the maximum length that flows may attain due to cooling effects [5]. This expression can be recast to estimate the maximum length attainable for flows adding to the accumulation of an individual volcanic edifice for specified effusion rates, slopes, and so on. One consequence of this behavior is that any recurring effusion rate during edifice construction can result in volcanic edifices that are some multiple of the fundamental cooling-limited lava flow length [6].

Recurring effusion rate histories are predicted for eruptions from a shallow reservoir for a variety of reasons. Many eruptions on Earth follow a well-defined effusion rate curve of exponentially decreasing effusion with time [8] which can be related to variations in eruption driving pressures arising from the properties of the magma chamber, the country rock, and the magma rheology. A potential consequence of a changing effusion rate during an eruption was noted by Wadge [4] for Mount Etna: If the effusion rate increases or decreases with time during an eruption, the maximum length of the lava flow produced during that time correspondingly increases and decreases. This behavior can be understood in terms of the *Gz* number and cooling-limited behavior outlined above. Variation in E cause the critical value of *Gz* to be attained for different lengths at different times during the eruption; the distribution of lengths accordingly reflects the variations in the shape of the effusion rate curve with time. The process can be expected to be complicated by the tendency for the near-vent flow field to move in well-defined levees or within crusted-over lava tube sections, but the general tendency will be to follow a growth history for individual eruptions similar to that shown in Figure 2.

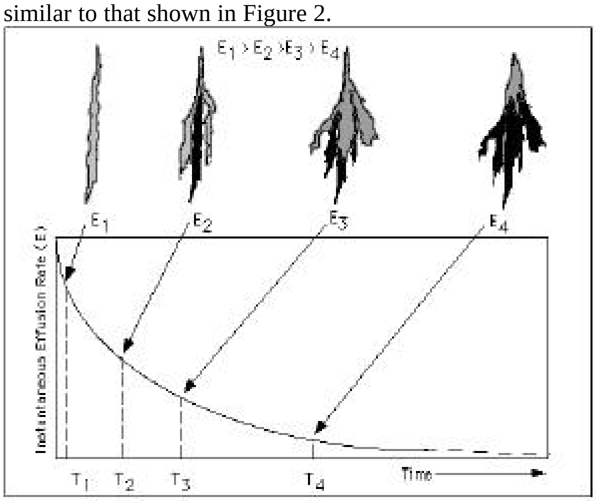

Figure 2. Variation in flow field shape and volume with exponentially declining effusion rate (E) for a single eruption during main phase of shield volcano construction. The gray portions of the field represent flows that are active during the indicated stages (T_1-T_4) of declining effusion.

Two additional ways in which variations in volume distribution may occur include variable arrangements of vents and displacements of the profile associated with central subsidence (including caldera formation) and subsequent edifice re-building. In order for variable arrangements of vents to account for the volume distribution of typical shield volcanoes, the vents must be distributed over the flanks. This can account for the distribution in some volcanoes provided that the vents are distributed in a narrow belt of a particular width for a particular average eruption volume distribution. Such patterns could arise from concentric fissure eruptions, but as a general mechanism, this does not explain the volume distribution in relatively simple edifices. There are few examples of concentric patterns of vents on the large Venus edifices. It is noted that small volcanoes and other evidence for small vents are frequently distributed over a broad region of the summit. This arrangement could arise from the relatively greater predicted depth of reservoirs associated with large volcanoes on Venus [7], owing to the greater dispersal of ascending magmas over the broader area of the underlying reservoir. Depending on the details of the distribution of such vents, the overall low profile and shallow slope of typical large volcanoes on Venus might originate from the correspondingly more distributed volume of accumulated individual eruptions from the edifices.

A premise in all of the above models is that all or most of the observed differences in profile characteristics are a result of variations in the distribution of erupted volumes. The role of intrusive inflation and caldera subsidence in the main edifice during cycles of inflation within the associated shallow magma reservoir may be important in some volcanoes. The magnitude of both inflation and subsidence must be dependent on the depth of the reservoir, and will be particularly influential only in cases where the reservoir resides in either the substrate very near the base of the volcano or within the edifice itself. Although magma reservoirs are commonly located at high levels within the edifice of volcanoes on Earth, and possibly on Mars, the depths to likely reservoirs on Venus [7] are predicted to almost always lie within the substrate. Accordingly, the influence of magma reservoir inflation on large volcano morphometry is predicted to be relatively minor.

From the above discussion, profiles departing from simple straight-sloped cones, in particular those with either steep summits or truncated forms, must represent the results of significant long-term changes or evolution in eruptive behavior of the edifice. Such changes might include late eruption of more differentiated magmas with rheological behaviors that differ from preceding flows, evolution of the magma reservoir such that magma driving pressures and effusion rates undergo long term changes, or structural changes within the volcano itself, perhaps as a result of caldera formation or even inflation of the volcano due to growth of the associated shallow magma reservoir. Detailed observation of the geologic characteristics of all of the individual edifices is necessary in order to determine which of these effects has been influential.

SUMMARY. The building of relatively straight-sloped shield volcanoes is direct evidence for the development of centralized, shallow magma chambers following an earlier, protracted phase of deeply-fed eruptions. Whereas many large volcanoes may initiate as regional effusions of relatively fluid and widespread lavas, the late stage development of shield suggests that centralized reservoirs develop over time

Measurements of the distribution of volume provide some information on the style of eruption during the late phases of edifice coinstruction. Although a variety of mechanisms may operate to distribute the volume in a manner consistent with straight-sloped shields, the variation in effusion during single eruptions is a simple mechanism that can result in the required volume distribution. Late stage activity of large shield volcanoes is evidence for the presence and behavior of shallow magma chambers within the elastic lithosphere operating during the culminating phases of the evolution of each center.

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